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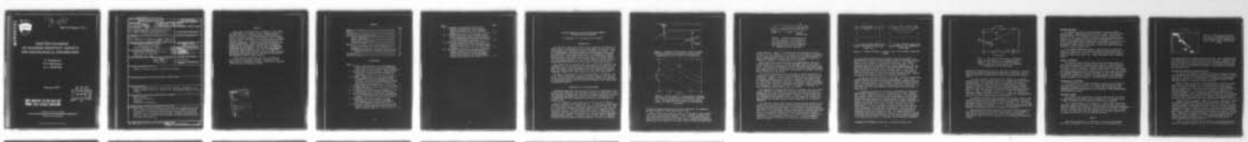

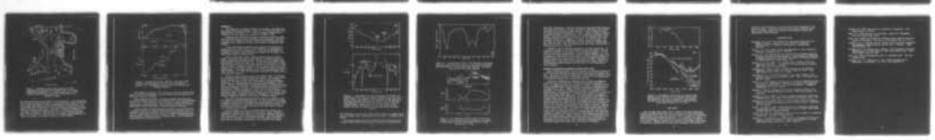

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SELECTED EXAMPLES OF RADIOHM RESISTIVITY SURVEYS FOR GEOTECHNICAL EXPLORATION

P. Hoekstra
P.V Sellmann
A.J. Delaney

January 1977

CORPS OF ENGINEERS, U.S. ARMY
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Measurements of ground resistivity using radio wave techniques have been made in support of several geotechnical projects. Examples of surveys conducted for locating and evaluating gravel deposits, for delineating permafrost, and for extrapolating subsurface information between drill holes are used to illustrate some advantages of ground and airborne surveys using this method.

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PREFACE

This report was prepared by P. Hoekstra, of R.M. Hardy and Associates Ltd. (Calgary, Alberta, Canada), and P.V. Sellmann, Geologist, of the Northern Engineering Research Branch, Experimental Engineering Division, and A.J. Delaney, Physical Science Technician, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was primarily provided by DA Project 4A762719AT24, *Design, Construction and Operation Technology for Cold Regions*, Task A2, *Soils and Foundation Technology for Cold Regions*, Work Unit 003, *Electromagnetic Methods for Subsurface Exploration* (QCR 1.07-CARDS 114). Additional support came from the U.S. Army Engineer Division, New England, the Alyeska Pipeline Service Co., and the U.S. Army Engineer District, Mobile Alabama.

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SELECTED EXAMPLES OF RADIOHM RESISTIVITY SURVEYS FOR GEOTECHNICAL EXPLORATION

P. Hoekstra, P.V. Sellmann and A.J. Delaney

INTRODUCTION

The purpose of this general report is to illustrate with several examples some of the advantages of the radiohm method of electrical resistivity mapping in obtaining geotechnical subsurface information. With the radiohm method, electrical resistivity is determined by measuring the properties of the various components of the groundwave of distant radio stations. These measurements can be made on the ground surface and from airborne platforms. An additional objective of this report is to provide some perception into the relative merits of ground and airborne resistivity surveys for various types of engineering projects.

The results used to illustrate the application of this relatively new geophysical tool are collected from surveys performed by CRREL over the last three years. Other investigators also have extensively used and tested the radiohm method and their data can be found in the following references (Culley et al. 1975, Hunter and Scott 1975, Scott 1975).

The range of applications of the radiohm method is, in general, similar to that of the galvanic resistivity method. However, the large increase in productivity of surveying with radiohm methods, in comparison to conventional methods, and the resulting decrease in cost make surveys of areas more feasible.

PRINCIPLES OF THE RADIOHM METHOD

Radiowaves propagating over the earth's surface are influenced by the nature of the subsurface, and from measurements on the radio surface wave, the resistivity of ground can be derived. Extensive treatises on theories of groundwave propagation are available (Wait 1962, Frischknecht 1973, Eliassen 1956) but only a descriptive discussion of the principles is presented here.

The electromagnetic field vectors in the far-field of a vertically polarized transmitter are shown in Figure 1. At the ground surface there are three field vectors: a horizontal, radially oriented electric field E_r, a horizontal, azimuthally oriented magnetic field H_ϕ, and a vertical electrical field E_z. All three field vectors decay in amplitude with increasing distance from the transmitter and are also affected by daily changes in the ionosphere and the nature of the path between transmitter and measurement station. In addition, the relative phase of these surface field vectors depends on these parameters. However, the evidence

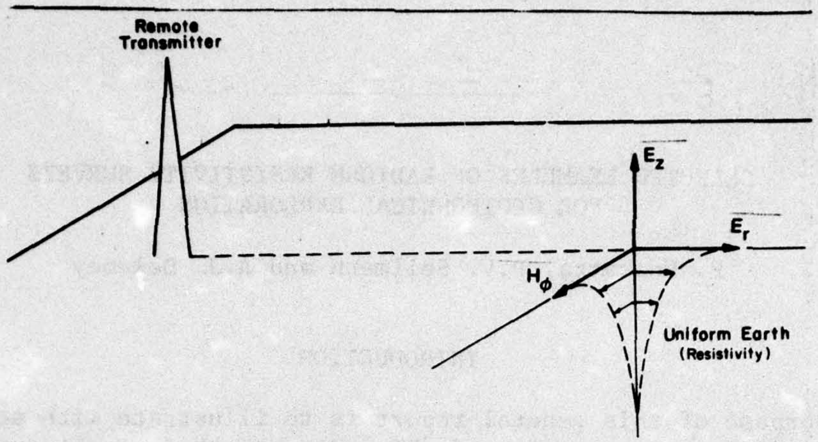


Figure 1. *Schematic representation of the electromagnetic field vectors of a vertically polarized radio ground wave in the far field of the transmitter.*

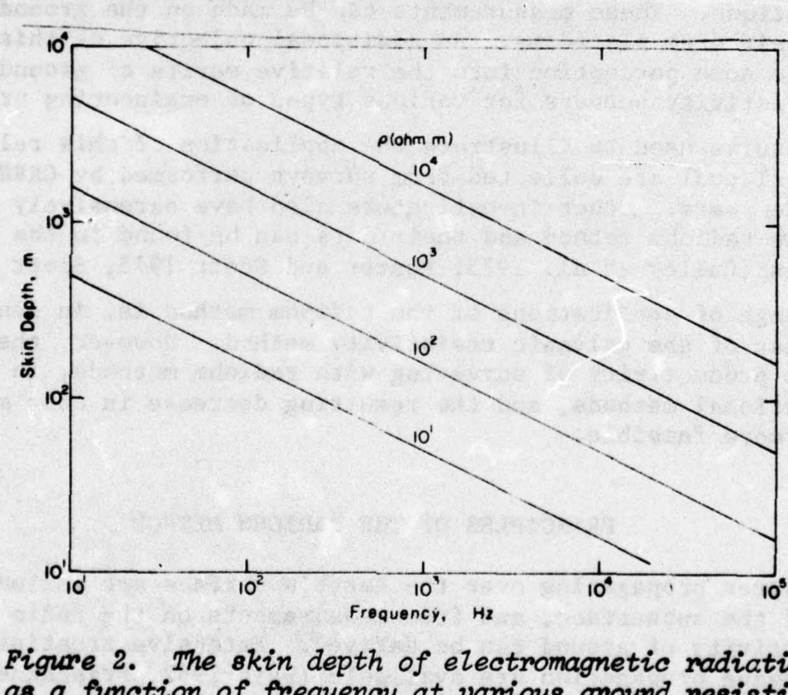


Figure 2. *The skin depth of electromagnetic radiation as a function of frequency at various ground resistivities. The common frequency ranges for very low frequency, low frequency and broadcast band transmitters are shown.*

is that all three field vectors are equally influenced by propagation path and ionospheric events (Frischknecht 1973).

Because of the large refractive index of the ground at radio frequencies, a near vertical wave propagates (even at grazing incidence) into the ground with horizontal vectors H_ϕ and E_r. In the ground the amplitudes of E_r and H_ϕ attenuate with depth, and the distance over which the field decays to 37 percent of its surface value is called the skin depth

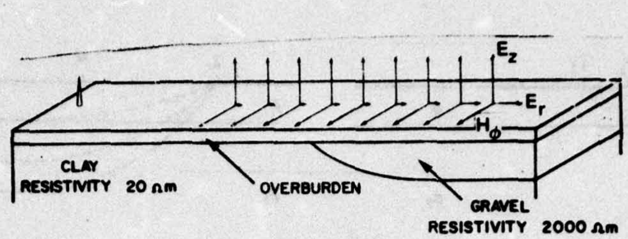


Figure 3. Schematic representation of the local changes in the magnitude of the electromagnetic field vectors of a vertically polarized radio ground wave when sections of ground of different resistivities are traversed.

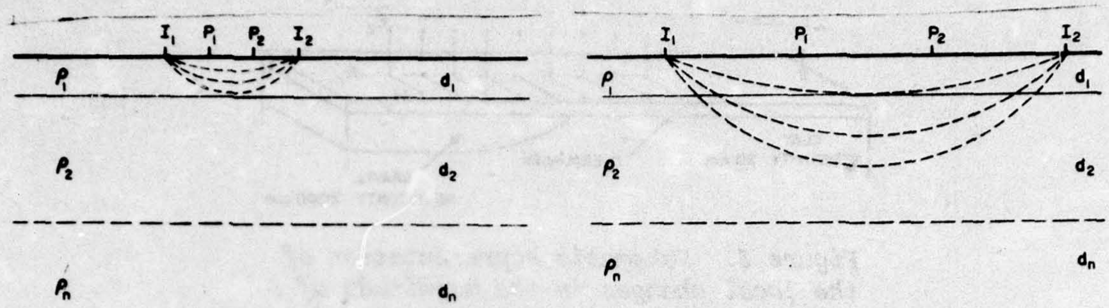
of the radiation. Figure 2 illustrates that the skin depth in ground uniform with depth depends on the frequency and the electrical properties of the ground. The skin depth of the radiation is an important parameter, since it approximately indicates the depth in the ground to which information is obtained by a measurement at the surface.

Both E_r and H_ϕ are continuous across the ground surface, but E_z is discontinuous, and in fact, E_z becomes negligibly small in the ground. E_r can, therefore, be measured by a dipole antenna above the earth's surface or in the ground by measuring the field strength between two probes; H_ϕ is measured by a coil located near the surface, and E_z with a vertical dipole antenna above the ground.

The basis for obtaining a local measurement of ground resistivity is illustrated in Figure 3, where a wave propagates over a change in ground conditions. Changes in local subsurface conditions cause perturbations in amplitude and phase of E_r, while local changes do not affect E_z and H_ϕ. Therefore, by measuring the ratio of E_r/H_ϕ (called surface impedance) or E_r/E_z (called wavetilt) a measurement is obtained of the local electrical resistivity. The factors of path of propagation, topography, and daily variations equally influence E_z, H_ϕ, and E_r.

The computation of ground resistivity is, at present, based on neglecting the effects of the dielectric constant of the ground on radio-wave propagation, and there are circumstances when such procedures may introduce substantial errors (Olhoeft 1975). However, in many applications the delineation of subsurface conditions is the object of a survey and a determination of the exact value of ground resistivity is of secondary importance.

Over the past decade several schemes for measuring the resistivity of ground from radiowaves by using the principles discussed above have been tried and two approaches have proven to be practical: one ground based technique (Collett and Becker 1967), and one airborne technique (Barringer 1972, 1973). The groundbased technique determines the surface impedance, (E_r/H_ϕ), by measuring E_r between two closely spaced probes (maximum spacing 10 m) with the array oriented in a radial direction towards the transmitter; H_ϕ is measured by a ferrite coil. A direct reading of apparent resistivity is obtained in commercially available equipment.



a. At close electrode spacing when current lines remain in the first layer (d_1).

b. At large electrode spacing when current lines are not confined to first layer.

Figure 4. Schematic diagram of current lines in the galvanic resistivity method.

The reason for measuring surface impedance, rather than wavetilt, in ground surveys is that in vegetated areas E_z is often disturbed near the surface, and is, therefore, an unreliable reference. The evidence is that H_ϕ is not affected by vegetation or local topography. In the Barringer Research Ltd. E-phase* airborne system, measurements are made above the vegetation and the tilt of the surface wave is recorded. Because of the long wavelength of the radiation used (> 10 km at VLF) a flight altitude of 60 m is equivalent to less than 0.01 wavelength at VLF, and the groundwave is still the dominant propagation mode. However, the resolution in mapping resistivity anomalies is reduced.

At VLF the radio stations used by the navies of the world effectively provide adequate worldwide coverage for measurements. Below 10 kHz natural noise has been used in audiomagnetotelluric measurements (Koziar 1975). To obtain adequate field strength at frequencies above 150 kHz may require placement of a temporary transmitter near a survey site. In some cases local LF and BCB stations are available that can provide a signal source.

In engineering geophysics the galvanic probe method of resistivity mapping finds extensive use, and its principles are briefly reviewed here to make a comparison with the radiohm technique. In the galvanic probe method, current is driven into the ground between two electrodes, and the resulting potential is measured between two other electrodes. Several electrode spacings and configurations are commonly employed; for example in the Wenner array, four electrodes are spaced in a line at equal intervals (Fig. 4). Current is driven through the outer two electrodes I_1, I_2, and the potential induced in the earth by this current is measured at the inner pair of electrodes. From the ratio of voltage and current the electrical resistivity of the ground can be calculated (Keller and Frischknecht 1966). To change the depth of exploration the spacing between the electrodes ("a" spacing) is altered. In the two layer situation of Figure 4a, the current lines are confined to the first layer at small "a" spacings, and the apparent resistivity

* *E-phase is a registered trade name of Barringer Research Ltd.*

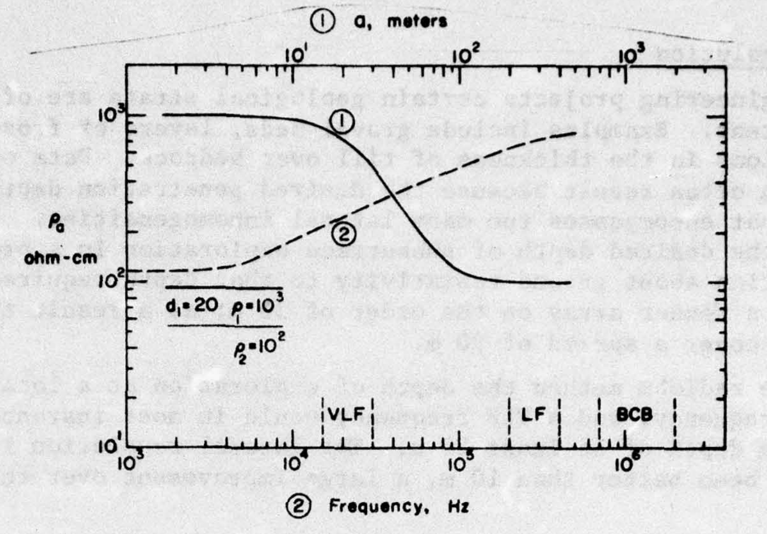


Figure 5. The apparent resistivity ρ_a calculated over a two-layer ground by two different techniques: 1) as a function of electrode spacing in a Wenner array (solid line), and 2) as a function of frequency in the radiohm method.

measured will approximately equal ρ_1; when the "a" spacing is increased (Fig. 4b) the current lines penetrate beyond the first layer, and the apparent resistivity measured will reflect the presence of the second layer.

In Figure 5 apparent resistivities are computed for a two-layer situation, both for the galvanic method with a Wenner array and for the radiohm method. For the Wenner array ρ_a is plotted as a function of electrode spacing (curve 1) and for the radiohm method as a function frequency (curve 2). There is clearly an analogy between frequency sounding in the radiohm method and altering the "a" spacing in a Wenner array. At short "a" spacings ρ_a equals ρ_1, at large "a" spacings ρ_a equals ρ_2, and at intermediate values $\rho_2 < \rho_a < \rho_1$. The corollary for the radiohm method is that at low frequency ($<10^4$ Hz) ρ_a is approximately equal to ρ_2, and at high frequency ρ_a approaches ρ_1.

An important difference between galvanic and radiohm surveys is that the latter can provide both phase and amplitude information. The phase difference between E_r and H_ϕ varies between 0 and 90°. In a two-layered situation a phase value between 0 and 45° indicates that $\rho_1 < \rho_2$, and when the phase is between 45° and 90°, $\rho_1 > \rho_2$. The phase information is often helpful in identifying the type of layering in the ground.

Through experience with resistivity surveying in various geological settings with both convetional and radiohm surveys, certain inherent advantages and disadvantages of each method have been recognized. The observations listed in the following are later illustrated by results of surveys.

Lateral resolution

In engineering projects certain geological strata are often of limited extent. Examples include gravel beds, layers of frozen ground and variations in the thickness of till over bedrock. Data of low quality can often result because the desired penetration depth requires a spread that encompasses too many lateral inhomogeneities. For example, if the desired depth of subsurface exploration in a project is 20 m, information about ground resistivity to that depth requires an "a" spacing in a Wenner array on the order of 30 m; as a result the entire array will cover a spread of 90 m.

In the radiohm method the depth of exploration at a location depends on frequency, and a VLF frequency would in most instances give an exploration depth of at least 20 m. The lateral resolution in field trials has been better than 10 m, a large improvement over the galvanic method.

Contact resistance

The galvanic probe technique requires good electrical contact between current probes and the ground, since often 10 to 100 milliamperes of current is required to flow through the galvanic current contacts. Good probe contact is difficult to obtain under certain field conditions, e.g. when the ground is frozen, consists of hard rock, or is snow covered. The radiohm method measures the field strength in the ground, and the input impedance between the probes is 10^8 ohms, 0.5 μμF. Low resistance contact is, therefore, not required and measurements can be obtained by laying the probes on the surface, or inserting them in the snow cover.

Productivity of surveying

The productivity of radiohm resistivity surveying at one frequency (VLF) has been at least a factor of 10 higher than galvanic surveys. Even when soundings are made at up to 10 different frequencies, as in audiomagnetotelluric measurements, the productivity of the radiohm method exceeds galvanic surveys.

Exploration depth

The galvanic probe method has the decided advantage that any depth of exploration can be chosen by merely changing the "a" spacing, and as a result, detailed data as a function of depth can be obtained.

In the radiohm method one is limited to a few available frequencies. Presently commercial equipment is readily available at VLF, and LF equipment has recently been constructed. Results with field portable audiomagnetotelluric equipment have also been reported (Koziar et al. 1975). Clearly the next few years must bring some improvement in equipment availability to enlarge the versatility of the radiohm technique.

RESULTS

Resistivity techniques for subsurface exploration are successful only when the different rock and soil strata to be mapped differ in

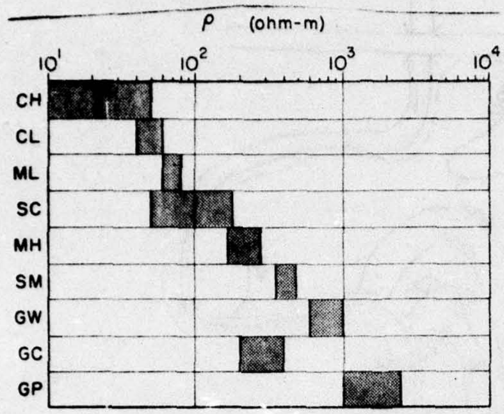


Figure 6. The resistivity range of soil types as described by the Unified Engineering Soil Classification System (after Hoekstra and Delaney 1973).

electrical resistivity from surrounding materials. These parameters must be considered before a resistivity survey is undertaken. However, even when substantial resistivity contrasts exist, successful mapping of substrata by geophysical techniques employed at the surface is not assured. How well strata can be mapped also depends on their depth of occurrence and layer sequences.

<u>Location and detection of gravel deposits</u>

In Figure 6 the resistivity ranges of several soil types, described by using the Unified Engineering Soil Classification, are shown. Gravels (GW, GC, GP) can often be distinguished from other soils by resistivity techniques, although it can be difficult to distinguish between sands (SM) and gravels on the basis of resistivity only.

Figure 7 shows a resistivity contour map based on a VLF (17.8 kHz) ground survey in Plainfield, N.H. The purpose of the survey was to locate an aquifer in gravel that had the potential of being recharged from the nearby brook. The study area is situated in the flood plain of the Blow-Me-Down Brook. The flood plain is underlain primarily by alluvial sediments. These sediments apparently range from well sorted to poorly sorted gravels. Radiohm measurements were made at 75 locations at 25-m intervals by a two-man crew in 3 hours. The point resistivity data were later contoured to yield the resistivity map shown in Figure 7.

Several trends are apparent. Most of the area is relatively uniform in resistivity, with most values falling between 200 to 400 ohm-m. On the eastern margin of the study area, adjacent to the brook, an area of higher resistivity (500-900 ohm-m) occurs. Based on the type of information shown in Figure 6, values in excess of 500 ohm-m in unconsolidated sediments can often be associated with relatively clean sand and gravels. Also there is always the possibility that bedrock comes close to the surface. Subsequent exploration by digging a test pit revealed that the profile at N and S consisted of 2 ft of fine-grained material at the surface underlain by cleaner gravel to a depth in excess of 10 ft. Water rapidly flowed into the test pit.

Part of an esker several miles in length is located along the east bank of the Connecticut River just north of the town of Hanover, N.H.

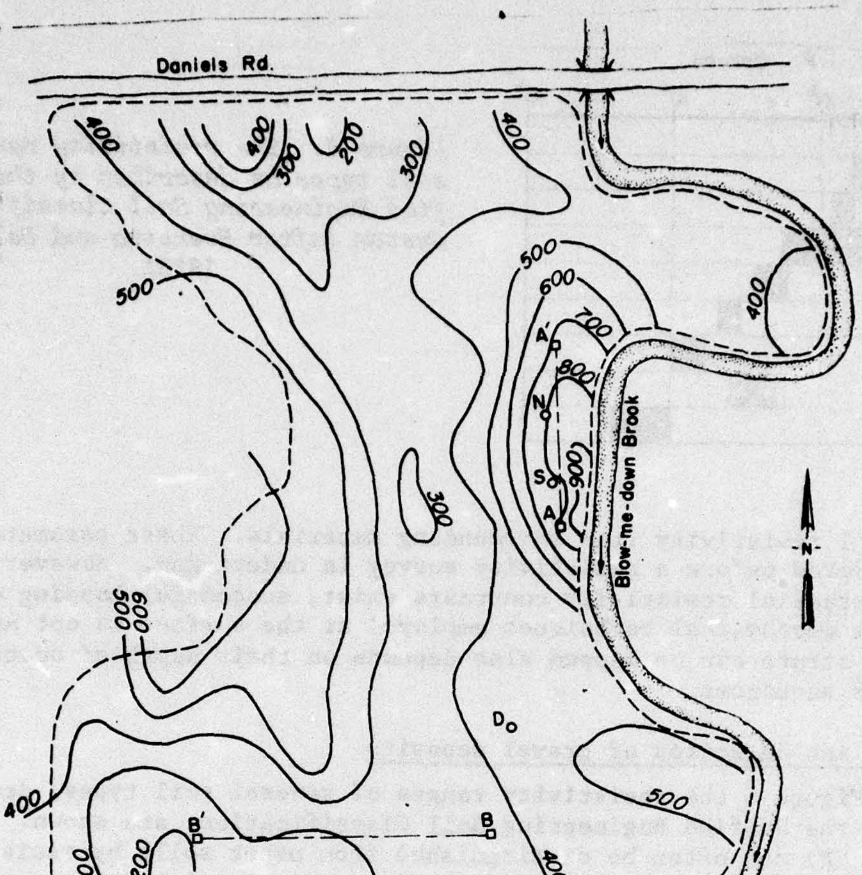


Figure 7. Resistivity contour map obtained from spot measurements on the ground with radiohm (VLF) at 25-m grid intervals in Plainfield, N.H. (after Delaney et al. 1974). Lines A-A' and B-B' are control probe lines while D is a borehole location.

The esker is used as a local source of sand and gravel. At one excavation site a radiohm resistivity survey at two frequencies was made over the top of the esker, and Figure 8 shows the resistivity profile obtained. The only ground truth available was the 40 ft exposure of gravel in the excavation north of the survey line. Lacustrine sediments including silt and clay can be found on the flanks of the esker. By computer modeling ρ_a and phase, an estimate of the thickness of the gravel deposit has been made. The survey is an illustration of how radiohm ground techniques can be used to estimate the volume of gravel in a known deposit.

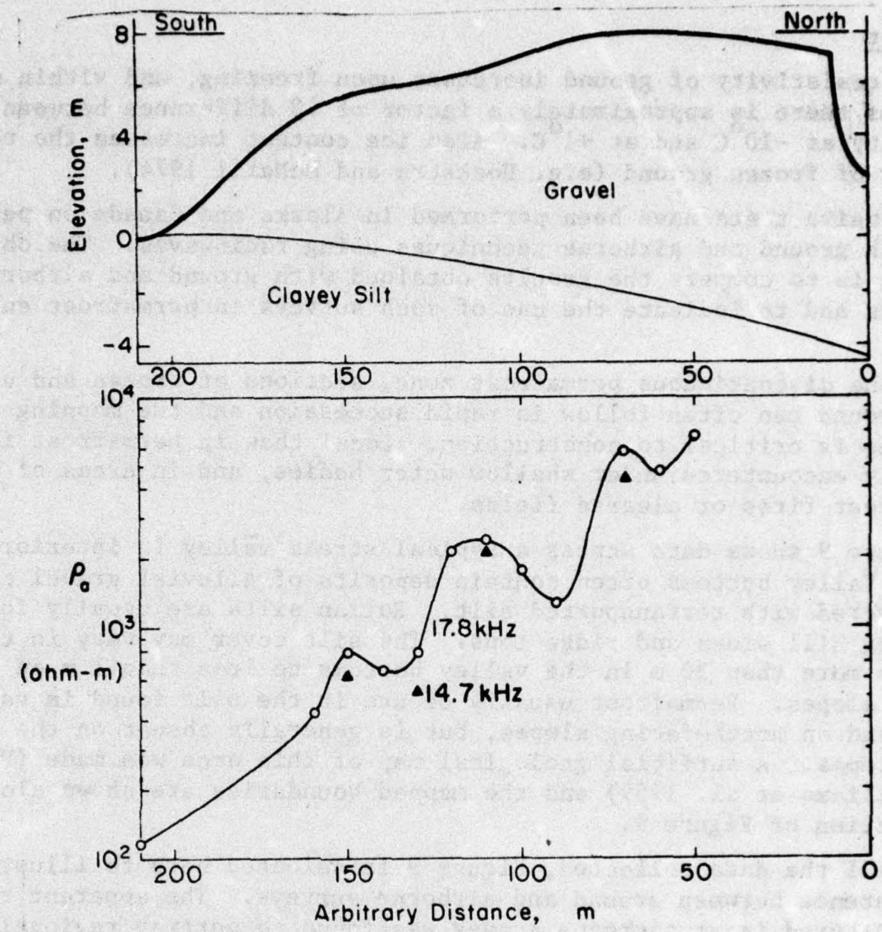


Figure 8. Resistivity profiles obtained on the ground with radiohm at two frequencies along the top of an esker in Hanover, N.H. The geological cross section was derived from computer modeling.

Both examples of Figures 7 and 8 illustrate that the radiohm method gives a very local measurement, allowing detailed lateral resolution of variation in ground conditions.

Gravel deposits which have no surface expression have been found with airborne E-phase surveys in the provinces of Ontario and Saskatchewan. Culley et al. (1975) report on detecting intertill gravel deposits with multifrequency airborne surveys. The resistivity anomalies of airborne mapping were further established by ground surveys and drilling.

Airborne surveys for detecting gravel deposits are of best use when a regional inventory of potential gravel sources is required, such as in areas where most gravel deposits with surface expressions have been extracted. Applications for ground surveys are found in evaluating identified deposits, in surveying areas of limited extent, or in following up anomalies found in airborne surveys.

Permafrost

The resistivity of ground increases upon freezing, and within most soil types there is approximately a factor of 10 difference between the resistivity at $-10^{\circ}C$ and at $+1^{\circ}C$. Also ice content increases the resistivity of frozen ground (e.g. Hoekstra and McNeill 1974).

Extensive tests have been performed in Alaska and Canada on permafrost with ground and airborne techniques using radiowaves. The objective here is to compare the results obtained with ground and airborne techniques and to indicate the use of such surveys in permafrost engineering.

In the discontinuous permafrost zone, sections of frozen and unfrozen ground can often follow in rapid succession and the mapping of boundaries is critical to construction. Local thaw in permafrost is frequently encountered under shallow water bodies, and in areas of previous forest fires or cleared fields.

Figure 9 shows data across a typical stream valley in interior Alaska. Valley bottoms often contain deposits of alluvial gravel commonly covered with retransported silt. Eolian silts are usually found blanketing hill sides and ridge tops. The silt cover may vary in thickness from more than 30 m in the valley bottoms to less than 1 m on ridge tops and slopes. Permafrost usually occurs in the silt found in valley bottoms and on north-facing slopes, but is generally absent on the south-facing slopes. A surficial geological map of this area was made (Péwé 1958, Williams et al. 1959) and the mapped boundaries are shown along the cross section of Figure 9.

Of all the data collected, Figure 9 is selected here to illustrate the difference between ground and airborne surveys. The apparent resistivity measured in an airborne survey was found to portray regional trends; the 500 ohm-m contour often corresponded to the boundary between Qf and Qsu, i.e. between frozen and unfrozen ground (Hoekstra, et al. 1974). However, local patches of thawed ground occur in the large frozen surficial geological unit, Qsu. The sharply defined resistivity lows in the profile of Figure 9 obtained by a ground survey were observed to correspond to surface expressions of thaw, such as cleared fields, small ponds and creeks. The regional trends between ground and airborne values along the profile of Figure 9 agree, but depressions in the permafrost of small dimensions (100 m^2) are not seen in airborne surveys.

The choice between ground and airborne surveys in permafrost areas will depend on the engineering objective. If the objective is to obtain a regional distribution of permafrost for town planning or for selecting preliminary locations of facilities, airborne surveys may be best. On the other hand the local detail required in the construction of pipelines demands ground surveys.

Another example of the use of radiohm resistivity surveys is in locating year-round water supplies in the Arctic. Figure 10 shows a resistivity traverse over a channel of the braided Sagavanirktok River near pump station 2 of the Trans-Alaska Pipeline. The river freezes to the bottom in the winter, but subbottom zones may remain unfrozen in some channels, offering the possibility of a permanent water supply.

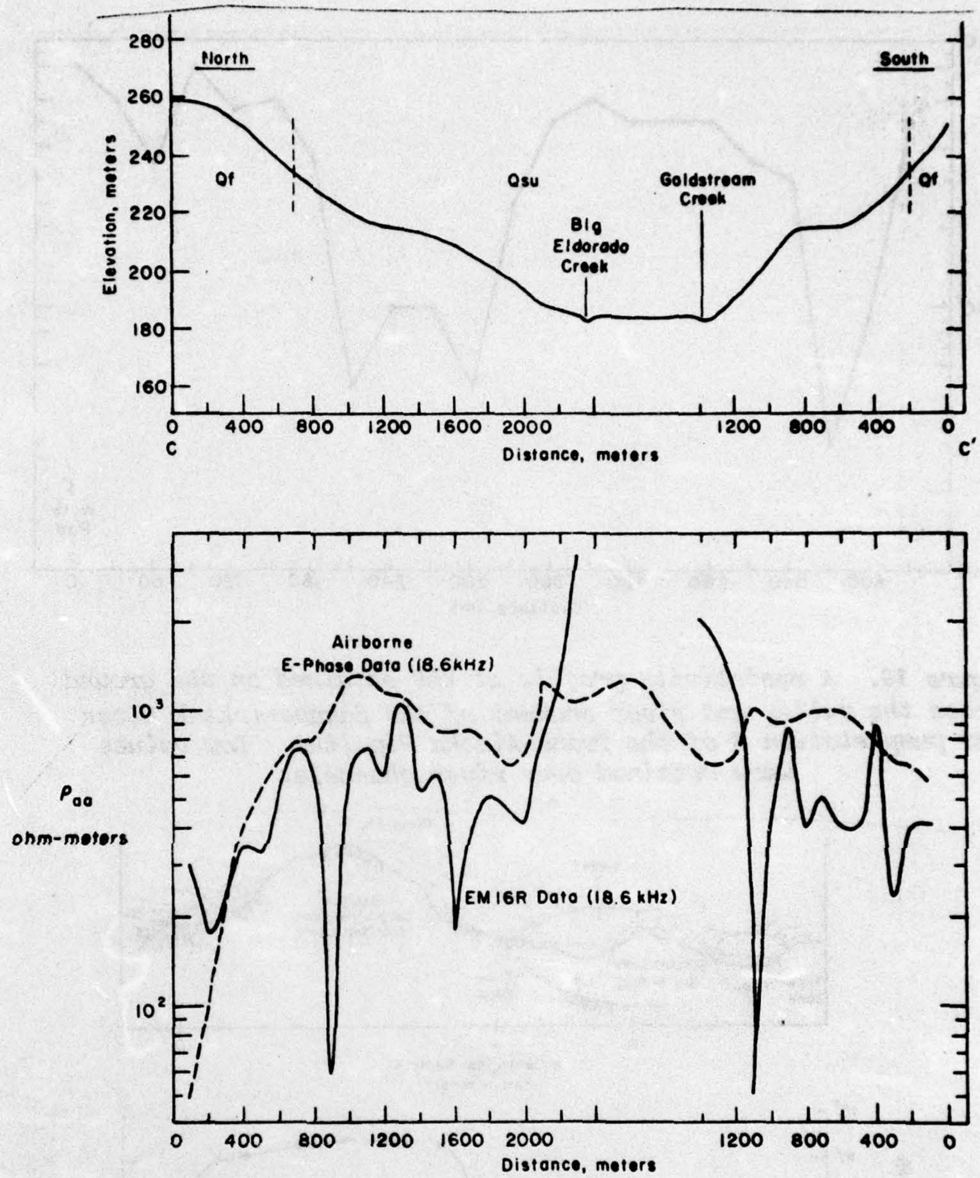


Figure 9. A comparison of ground and airborne VLF apparent resistivities along a traverse across Goldstream Valley near Fairbanks, Alaska. Also shown are the topography of the terrain and the mapped surficial geological boundaries. The unit Qsu indicates permafrost in the silt cover, and the unit Qf indicates unfrozen ground. (EM16R refers to the model number of the Geonics unit used for measuring resistivity during the ground survey.)

The resistivity low over the channel probably indicates a thawed layer, and this location upon further exploration may yield a permanent water supply.

Electrical grounding for fault clearance and installation of impressed current anodes requires ground conditions of relatively low

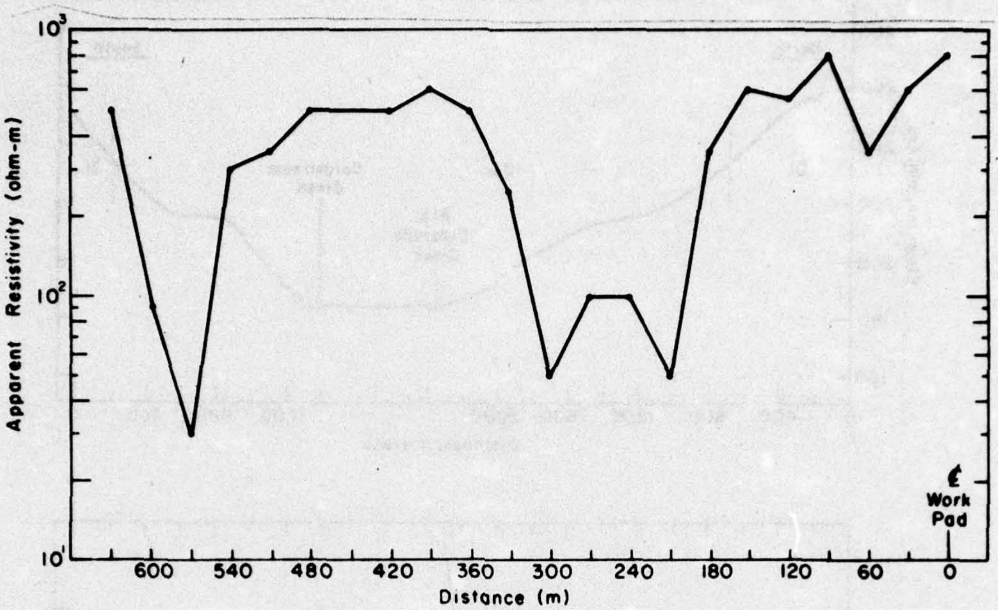


Figure 10. A resistivity profile at VLF obtained on the ground across the valley and river channel of the Sagavanirktok River near pump station 2 of the Trans-Alaska Pipeline. Low values were obtained over river channels.

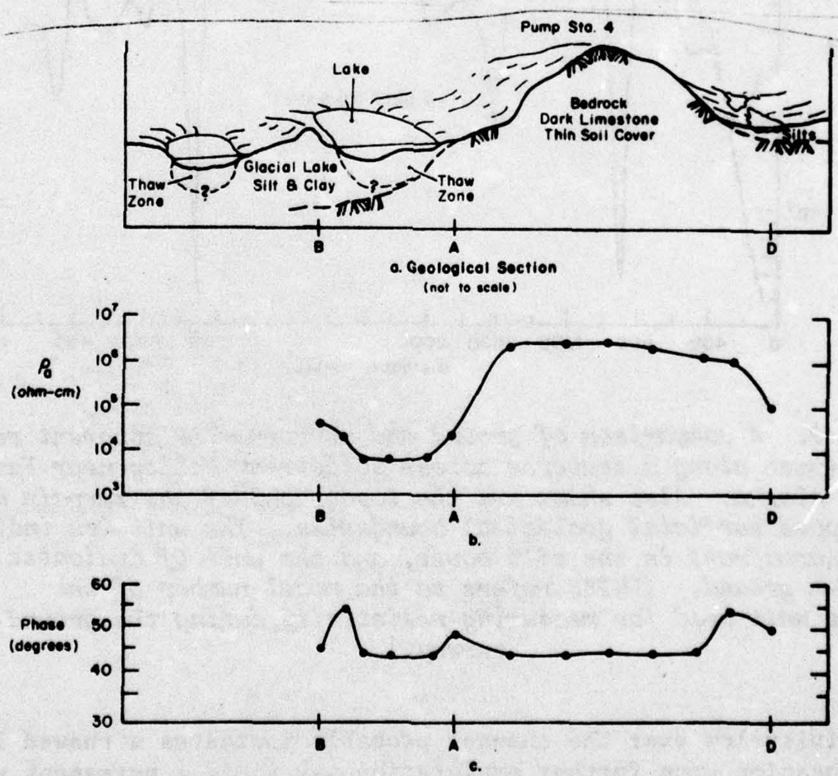


Figure 11. An idealized geological cross section and a radiohm (VLF) resistivity profile obtained on the ground at pump station 4 of the Trans-Alaska Pipeline (after Sellmann et al. 1974).

electrical resistivity. Along many sections of the Trans-Alaska Pipeline the ground was dominantly of high resistivity (>1000 ohm-m), and surveys were made in the vicinity of pump stations to locate subsurface strata of conductive ground (Sellmann et al. 1974). Figure 11 shows an apparent resistivity profile at pump station 4 and an idealized geological cross section. The pump station is located on a frozen limestone knoll where the resistivities are in excess of 10^4 ohm-m. At the base and to the northwest of this knoll, sediments of glacial lacustrine origin, silts and clays, are found, and thaw under the lake results in resistivities less than 100 ohm-m. With the radiohm method the survey could be made in winter over the ice on the lake.

Permafrost cannot always be recognized by its high resistivity. An illustrative example is the North Slope of Alaska near Barrow. Radiohm resistivity surveys on the ground at VLF gave values between 10 to 150 ohm-m on the frozen tundra within a 20-mile radius of Barrow. The cause of these low resistivities is brine layers in frozen marine sediments at shallow depth (5 m to 20 m). The surface layers, consisting of high ice content ground, have resistivities in excess of 10^4 ohm-m. Radiowaves undergo little attenuation in such high resistivity surface layers, and VLF measurements mainly reflect the resistivity of the frozen brine-soaked sediments.

<u>Extrapolating subsurface information between drill holes</u>

Many engineering endeavors require knowledge of subsurface conditions, and drilling and sampling are often required to obtain the necessary detail. Any project can only accommodate a certain number of holes, and the proper spacing and location of drill holes, as well as the extrapolation of information between them, is therefore important.

Resistivity techniques can sometimes help to reduce the number of holes and allow extrapolation of subsurface information between drill holes. An example is used from a survey in support of geotechnical work for the proposed Dickey-Lincoln hydroelectric project in northern Maine (Sellmann et al. 1975). Figure 12 shows a resistivity traverse and a geological cross section, obtained by drilling, of an abutment of the proposed dam. From station 200 to station 600 the resistivity varies randomly from 4000 to 8000 ohm-m. These values are typical of competent slate without much till overburden. Till covers much of the bedrock in northern Maine, and because the till in this situation has a lower resistivity than the underlying slate, an overburden of till depresses the apparent resistivity. When the till overburden increases in thickness at station 600, the resistivity decreases accordingly and the thickness of till at each location can be estimated from computer modeling. Computer modeling can be particularly effective when the resistivities of the strata, in this case slate and till, are known. At station 900 the silts and clays of the St. John River Valley are first encountered, and again the resistivity clearly reflects this by declining sharply. The resistivity traverse, completed in 3 hours, provides a firm foundation on which to base a drilling program, because locations similar in resistivity at VLF will most likely have similar ground conditions down to the depth of exploration of at least 20 m. Also, subsurface conditions can be extrapolated between drill holes with some degree of confidence.

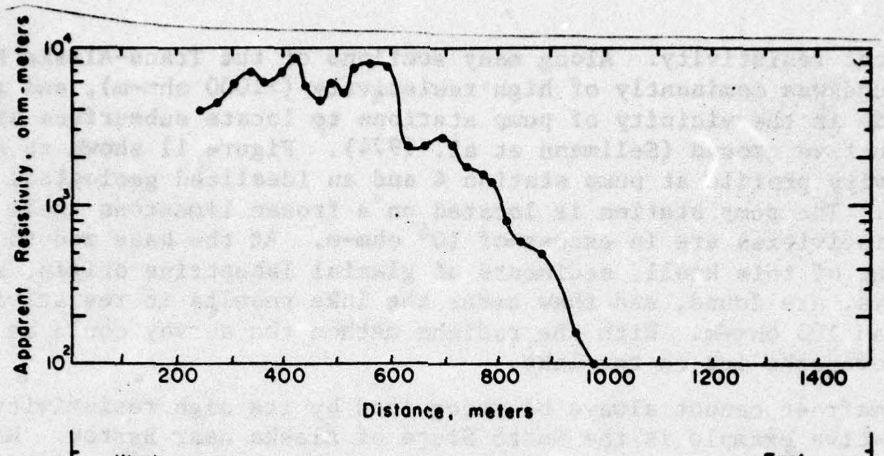


Figure 12. The apparent resistivity with radiohm (VLF) measured along a section of the proposed Dickey-Lincoln dam centerline (top) and the geological cross section obtained by the New England Division from several drill holes (after Sellmann et al. 1975).

CONCLUSIONS

Over the past three years, work in support of several engineering projects has demonstrated that ground and airborne resistivity surveys using radiowaves can lower the cost and improve the quality of subsurface exploration in some geological settings. It is, however, no panacea. A careful assessment of what information can be derived must be made for each project. Computer modeling can be helpful in deciding on the merits of resistivity mapping when the approximate geological distribution of

materials, both horizontally and vertically, and the properties of the strata are known. The recent extension of available commercial equipment to frequency ranges other than VLF should greatly improve the versatility of these methods.

LITERATURE CITED

Barringer, A.R. (1972, 1973) Geophysical exploration method using the vertical electric components of a VLF field as a reference. Canadian Patent no. 1,261,732; USA Patent No. 3,594,633 and 3,763,419.

Collett, L.S. and A. Becker (1967) Radiohm method for earth resistivity surveying. Canadian Patent No. 795,919.

Culley, R.W., F.L. Jagodits and R.S. Middleton (1975) E-Phase system for detection of buried granular deposits. Paper presented at *Symposium on Modern Innovations in Subsurface Exploration*, 54th Annual Meeting of Transportation Res. Board, Wash., D.C.

Delaney, A.J., D.A. Gaskin, P.V. Sellmann and P. Hoekstra (1974) New radio-wave resistivity techniques for locating groundwater supplies. CRREL Technical Note (unpublished).

Eliassen, K.E. (1956) A survey of ground conductivity and dielectric constants in Norway within the frequency range 0.2-10 MC. *Geofs. Publ.* (Oslo), vol. 19, no. 11, p. 1-30.

Frischknecht, F.C. (1973) Electromagnetic scale model studies of geophysical methods using a plane wave source. Univ. of Colorado, Dept. EE, Ph.D. Thesis.

Guineau, B. (1975) Examples d'application de la methode magnetotellurique de prospection geophysique a l'étude de structures ou de formations geologiques situées sous un très faible recourrement. *Geophysical Prospecting*, vol. 23, p. 104-124.

Hoekstra, P. and A.J. Delaney (1973) Ground resistivity survey in the area of the Tennessee-Tombigbee Waterway. CRREL Special Report 191, AD 767246.

Hoekstra, P. and D. McNeill (1973) Electromagnetic probing of permafrost. *Permafrost, Sec. Int. Conf, North American Contribution*, NAS, p. 517.

Hoekstra, P., P.V. Sellmann and A.J. Delaney (1974) Ground and airborne resistivity surveys of permafrost near Fairbanks, Alaska. *Geophysics*, vol. 40, August.

Hunter, J.A. and W.J. Scott (1975) Application of geophysical techniques in permafrost regions. The Geological Society of Canada (28th Annual Meeting) Waterloo, Canada (Abstract).

Keller, G.V. and F.C. Frischknecht (1966) *Electrical methods in geophysical prospecting*. New York: Pergamon Press.

Koziar, A., J.R. Rossiter, Y.D. Redman and D.W. Shangivag (1975) Electromagnetic probing of permafrost. The Geological Society of Canada, 28th Annual Meeting, Waterloo, Ontario (Abstract).

Olhoeft, G.R. (1975) The electrical properties of permafrost. Ph.D. Thesis, Univ. of Toronto.

Péwé, T.L. (1958) Geology of the Fairbanks, Alaska (D-2) Quadrangle. U.S. Geol. Survey, Map CQ-110.

Scott, W.J. (1975a) VLF resistivity (radiohm) survey, Agricola Lake area, District of MacKenzie. GSC, Report of Activities, Part A, p. 223.

Sellmann, P.V., P. Hoekstra and A.J. Delaney (1974) Electrical resistivity measurements at Alaska pipeline pump stations 1 through 5. CRREL Internal Report 406.

Sellmann, P.V., A.J. Delaney and P. Hoekstra (1975) Radiowave resistivity measurements in northern Maine for identifying bedrock type. CRREL Special Report 238, AD 017944.

Wait, J.R. (1962) *Electromagnetic waves in stratified media.* New York: Pergamon Press.

Williams, J.R., T.L. Péwé and R.A. Paige (1959) Geological map of Fairbanks, D-1 Quadrangle. U.S. Geol. Survey Map CQ-124.